# DESIGN OF A LABORATORY SCALE BIOREACTOR FOR TREATING LANDFILL WASTE

M. J. Myers, A. D. Christy, O. H. Tuovinen

**ABSTRACT.** *This article documents the design and construction of a laboratory-scale (1.5 $m^3$) bioreactor system that can be used to simulate anaerobic microbial processes in landfills. This design has use in feasibility studies of landfill bioreactor operation and management technologies. The system was designed for gas collection and to provide leachate recirculation and moisture addition to accelerate biodegradation. Two bioreactors were loaded with fresh municipal solid waste (MSW) from a sanitary landfill and instrumented to monitor temperature, mass, leachate production, and preferential flow of leachate within the heterogeneous material. One of the bioreactors received a layer of municipal sewage sludge to assess the feasibility of co-disposal. In this initial phase of the study, the decomposition of landfill waste in the bioreactors was monitored over 15 months. The decomposition was not intense, and it was concluded that microbial biodegradative activity was limited by a high C:N ratio and a high proportion of paper and plastic (ca. 70%-wt/wt) of the MSW.*
***Keywords.*** *Anaerobic biodegradation, Bioreactor, Landfill, Leachate, Municipal solid waste, Sanitary landfill, Sewage sludge.*

In most localities, municipal solid waste (MSW) is disposed of via dumping at a sanitary landfill. The most common method for landfilling operations is to entomb or encapsulate the waste using engineered containment systems including caps, liners, and leachate collection per the Resource Conservation and Recovery Act Subtitle D requirements (Code of U.S. Federal Regulations, 40 CFR Part 258). By minimizing the access of water infiltrating the landfill, this management technique leads to a reduction in the volume of leachate produced. However, low moisture (< 40%) is prohibitive to the biological decomposition of MSW at the landfill.

Long-term releases of leachates from closed landfills testify to the finite lifetime of past engineered closure technologies. Loss of the physical integrity of liners (natural clays and/or geosynthetics) makes long-term landfill containment suspect. Landfill closure caps can eventually fail, allowing infiltration into the landfill waste and subsequent leachate releases. Leaking landfills pose a persistent threat to both surface and groundwater resources and thereby to human, animal, and plant life.

Innovative ways are needed to operate landfills. One new approach is to transform the relatively static landfill into a solid state bioreactor in an effort to promote anaerobic biodegradation. Pacey et al. (1999) define the bioreactor landfill as ". . . a sanitary landfill that uses enhanced microbiological processes to transform and stabilize the readily and moderately decomposable organic waste constituents." MSW and other landfill waste are susceptible to biological decomposition in direct analogy to composting systems. Landfills are largely anaerobic environments, which makes the microbial communities different from those in composts because composting is usually practiced with bulk aerobic conditions. MSW is composed of heterogeneous materials which vary greatly in their potential for anaerobic decomposition (Owens and Chynoweth, 1993).

Raw and composted sewage sludge has been used to enhance biodegradation of landfill materials and thereby to stimulate methanogenesis (Stegmann and Spendlin, 1989; Reinhart and Townsend, 1997). In the U.S., regulations vary by state. For example, in California, sludge can be landfilled at a maximum regulated ratio of one part sludge to five parts MSW (Tchobanoglous et al., 1993). In laboratory-scale landfill bioreactor systems, seeding or inoculation with sewage sludge or biosolids has been used to accelerate the startup phase (Watson-Craik and Sinclair, 1995; Reinhart and Townsend, 1997). However, ongoing co-disposal of sludge with MSW to enhance decomposition of landfill materials has been studied only to a limited extent. Anaerobic sewage sludge has been used as a seed to initiate methanogenesis in laboratory-scale MSW columns (Pohland et al., 1992; Reinhart and Townsend, 1997). Sewage sludge application to a 20 000 $m^3$ landfill test cell in Brogborough, U.K., was reported to increase landfill gas yield and quality (Reinhart and Townsend, 1997).

Several studies have been conducted utilizing leachate recycle as a means of controlling or increasing the moisture content of the landfill contents. The experimental scales of these studies have ranged from laboratory columns to controlled landfill cells (Pohland, 1975, 1980; Leckie et al., 1979; Buivid et al., 1981; Kinman et al., 1987; Barlaz et

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al., 1989; Bogner, 1990; Townsend et al., 1994, 1995; Reinhart and Townsend, 1997). Although the conclusions in these studies differ on some accounts, there is a consensus that increasing the moisture content to field capacity enhances the biodegradation of MSW. Using landfills as bioreactors at 40% moisture content or more will help decompose MSW faster than in conventional operations.

Compared to conventional entombment, landfill bioreactor technology has multiple perceived benefits. These include faster biotransformation rates, reduction in the volume of MSW, and facilitated recovery of landfill gas, both for use as a biofuel and to control the release of greenhouse gases (Pacey et al., 1999). Construction of on-site leachate treatment, storage, and recirculation systems minimizes the demand for leachate treatment at local wastewater treatment facilities and thus decreases the likelihood that residuals of recalcitrant compounds are passing through the treatment system to receiving watersheds. Decreasing the time to stabilization shortens the duration of post-closure operations, thus reducing costs and environmental liability.

The objective of this work was to design and construct a laboratory scale landfill bioreactor that could be used to assess and quantify biodegradation of landfilled MSW. Various landfill bioreactor designs including columns and bins have been tested for sewage sludge amendment and for assessing the fate of recalcitrant and xenobiotic molecules. The bioreactor volumes used in other studies have been relatively small (usually up to 0.03 $m^3$), making it difficult to mimic MSW heterogeneity and preferential flowpaths under landfill conditions. MSW needs to be shredded to fit small-scale systems. However, shredding of waste is currently economically infeasible for full-size landfills. Therefore, one of the design criteria for this study was to use a scale where unshredded MSW could be used. Other problems typically encountered in small-scale laboratory bioreactor landfills involve heat and gas transfer. Small volume bioreactors lose too much heat due to their large surface area to volume ratios. It also can be difficult to maintain an air-tight anaerobic environment within the bioreactor while still providing piping for gas collection, leachate collection, and water application.

For the present work, the design size of the laboratory scale bioreactor was increased to about 1.5 $m^3$ with improved accessibility to leachate collection and instrumentation. This made it the largest documented indoor non-column laboratory landfill apparatus which by its size and configuration allowed the use of unshredded MSW. Other novel design objectives were the use of multiple drain ports to assess preferential flow of leachate, placing the bins on an elevated platform to improve access and safety, use of an in-line flow-through cell for leachate measurements, incorporation of a grid pattern subirrigation system for leachate application, and use of load cells for monitoring mass changes.

During the time course of this experimental study, the parameters that needed to be controlled were moisture content of the MSW, flow rate of the applied water and leachate solution, and the pH of the water and leachate solution. Parameters that needed to be measured were temperature, mass, and the quantity and chemical composition of the leachate and gas. An initial characterization of the actual MSW used was also required.

## System Design and Experimental Procedure

### Bin and Scaffolding Construction

Two identical landfill bioreactor bins were constructed for this study, each with a total volume of 1.5 $m^3$ (2.0 $yd^3$) and external dimensions of 91 cm × 183 cm × 91 cm. The cross-section of the bin is diagrammed in figure 1. Figure 2 shows the completed laboratory system. Each bin was constructed of galvanized 14 gauge steel with a 7.5-mm-thick, 60 cm × 78 cm Plexiglas viewing window. The bins were modified from use in soil infiltration studies; additional details on the construction of the original, unmodified bins can be found in Ward et al. (1983).

Wooden scaffolding including platform, stairway, and handrails (fig. 2) was constructed to allow researchers access to all levels of the apparatus and to meet OSHA safety requirements.

A large, 3 m × 3 m, 1.1 $m^3$/s (2300 cfm) polypropylene overhead exhaust hood was placed above the bins to capture fugitive odors and landfill gases (fig. 2); it was constructed of high density polyethylene (HDPE) to prevent corrosion. The exhaust fan ran continuously as an additional safety measure.

To measure preferential flow of landfill leachate, the bottoms of both bins were divided into eight sections, and 2.5 cm of concrete was poured into each section and sloped towards the drain associated with that area. To mimic field conditions, the MSW was to be intentionally compacted. To withstand this compaction, concrete with a 3:1 sand/cement ratio was selected. This concrete mixture also allowed contouring of the bottom during construction and minimized shrinkage during curing.

Above the concrete, a 1.52 mm HDPE flexible membrane liner was installed, followed by geonet drainage

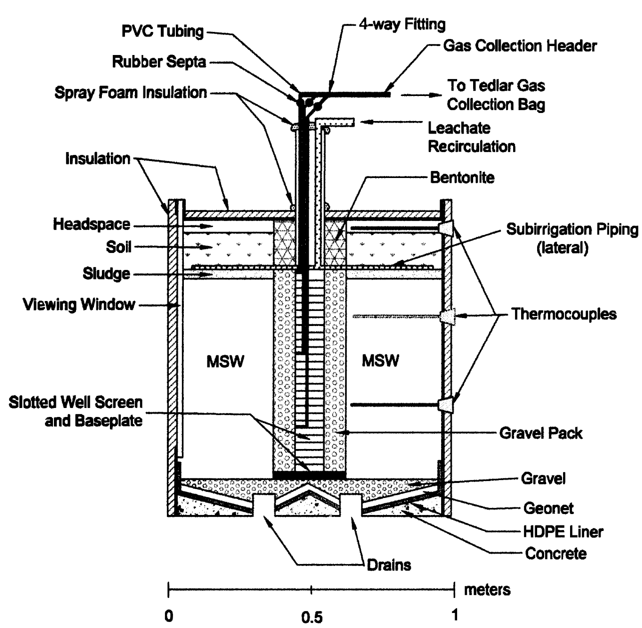



**Figure 1–Schematic cross-section of landfill bioreactor bin B.**

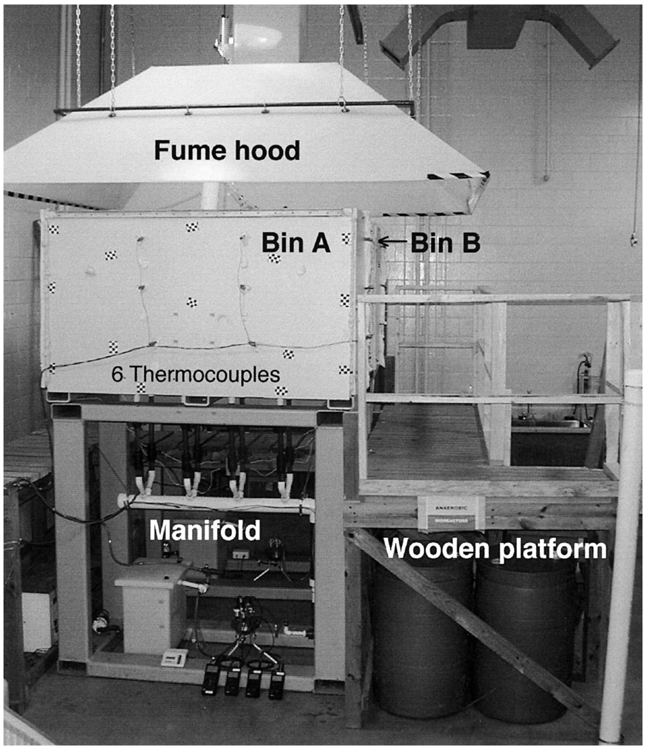



**Figure 2–Landfill bioreactor bins.**

layer. A 15-cm-deep layer of 40-mm effective size non-reactive (limestone free) gravel was then installed to protect the drainage layer and to facilitate leachate drainage. Once the leachate contacted the drainage layer, it flowed towards the nearest drain. After installation of the bottom liner and drainage system, the airspace volume of each bin was reduced from the initial 1.5 $m^3$ to 1.26 $m^3$.

### Bin Loading

Fresh MSW material to be placed in the bins was obtained at a local operating sanitary landfill (Solid Waste Authority of Central Ohio, Franklin County, Ohio). The empty bins were transported by flatbed trailer to the landfill. As the incoming collection vehicles and larger tractor trailers unloaded at the working face of the landfill, random front-end loader buckets full of MSW were placed in the bins. The waste was not shredded. No effort was made to remove the ripped plastic garbage bags nor was any other sorting performed upon the material placed in the bins with the exception of one large wicker chair.

For this study, compaction of the material in the bins was accomplished using the front-end loader bucket, because of equipment availability and ease of field implementation. An alternative compaction method employing four hydraulic jacks to drive a steel plate against the MSW was initially considered, but would have been difficult to manipulate in the field. Disposable Tyvek® (non-woven polyethylene fiber) coveralls were worn by the workers as they loaded the material into the bins.

One MSW bin was used without sewage sludge amendment (bin A). The MSW in the other bin (bin B) was overlaid with a single layer of anaerobically digested sewage sludge (fig. 1) that had been dewatered by centrifugation. The ratio of MSW to sludge was 5:1 on a wet weight basis.

### Initial Characterization of MSW and Sludge

Samples of the MSW were collected before, during, and at the end of the bin filling operation, and were combined to yield a total composite volume of 0.21 $m^3$ (55 gal drum) for each bin. An arbitrary sample was manually collected from both bin composites and placed in a sealable 0.0005 $m^3$ plastic bag for elemental analysis using standard methods (APHA, 1998) and determination of cellulose, hemicellulose, lignin, and protein content using proprietary methods developed by Nalin Laboratory (Columbus, Ohio) for the pulp and paper industry. Prior to analysis, the samples were homogenized via grinding. The dewatered sludge used in bin B was analyzed by the Ohio Agricultural Research and Development Center (OARDC) Laboratory (Wooster, Ohio) using USEPA (1998) methods. The remainders of the two composite samples (from Bin A and Bin B) were combined, and manually sorted by visual characterization of the waste type. Each sorted waste fraction was tested for moisture content using the ASAE Standard for Grain Moisture Content (D245.4). The total amount separated for each waste fraction was tested except in the cases of paper and plastic where representative sub-samples were tested.

### Gas Extraction System

After filling each bin with MSW, a landfill gas extraction well was constructed of 10.2 cm O.D. schedule 40 PVC slotted well screen with a 10.2 cm O.D. PVC header. The complete assembly was manually inserted into the center of the bin until the well screen rested on a 20.3 cm O.D. PVC baseplate (1.3 cm thick) located 8 cm above the lower gravel-waste interface (fig. 1). The annular space around the well was then backfilled with gravel up to the soil layer. The gas extraction well screen was constructed of three 17.8 cm long vertical sections. Clear PVC tubing (1.6 cm O.D.) connected each section within the well to a collection header which was then connected to a detachable Tedlar sampling bag. Tee fittings with rubber septa were inserted in each of the three lines to enable gas samples to be retrieved from depths of 10.2 to 27.9 cm, 27.9 to 45.7 cm, and 45.7 to 63.5 cm beneath the cap. Thus, the gas extraction system could be used to collect gas samples from different depths and to quantify the total rate of gas production. Bentonite pellets were used to fill the annular space surrounding the gas extraction well above the gravel pack, between the upper soil-waste interface and HDPE cap liner. Upon installation, the bentonite was hydrated to seal the space. It was important to maintain hydrated conditions to ensure the seal's integrity over time.

### Subirrigation System

Water and leachate was applied at the soil-waste interface using a grid pattern subsurface irrigation piping network (fig. 3). The laterals and the sub-mains were installed directly on top of the MSW and covered with soil (fig. 1). Flexible high temperature 1.6 cm O.D. silicone tubing was used to allow for settlement. A series of 2-mm-diameter holes spaced 7.6 cm apart were drilled into each lateral.

### Containment and Insulation Systems

A 10.2 cm soil cover was placed above the MSW and subirrigation system, followed by 1.52 mm HDPE flexible

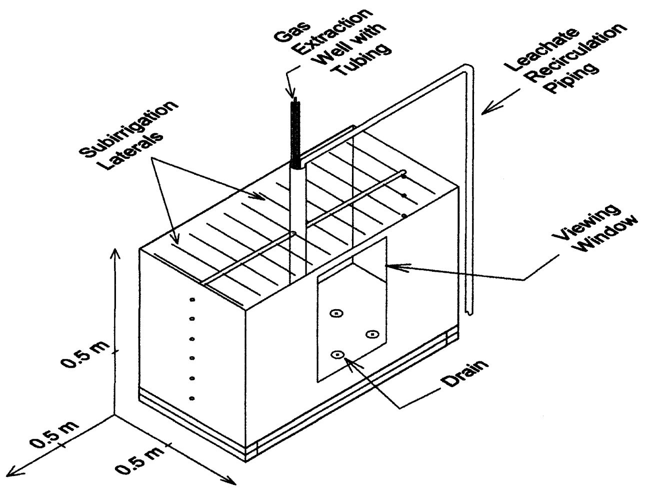


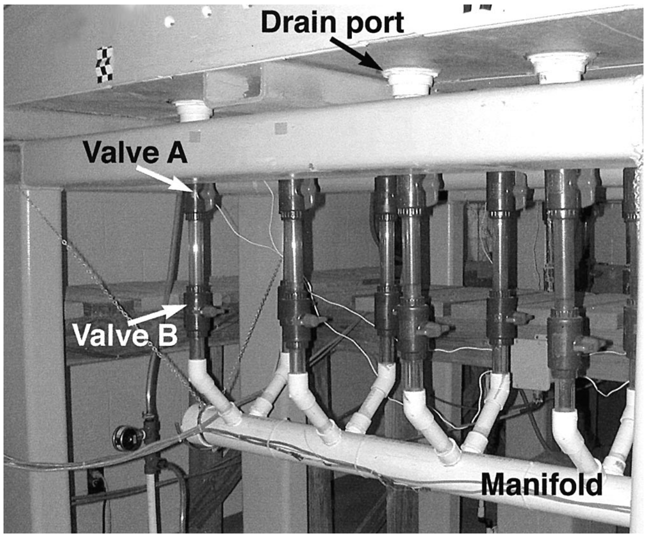

**Figure 3–Isometric of subirrigation piping system.**

membrane liner. This left an initial headspace of approximately 10.2 cm between the upper soil layer and the HDPE liner. Heat flow across the boundaries of the bin was controlled using insulation on all vertical sides and the top of the bin. Polystyrene foam board insulation (25 mm, R-value of 5) was affixed by copper coated stainless steel pins which were spot welded onto the bins. A removable insulation panel was placed over the Plexiglas window to allow visual observation of bin contents. To further seal the bins, expandable foam insulation was sprayed at the top of the gas collection well and at the junction between the gas well and the top of the bin.

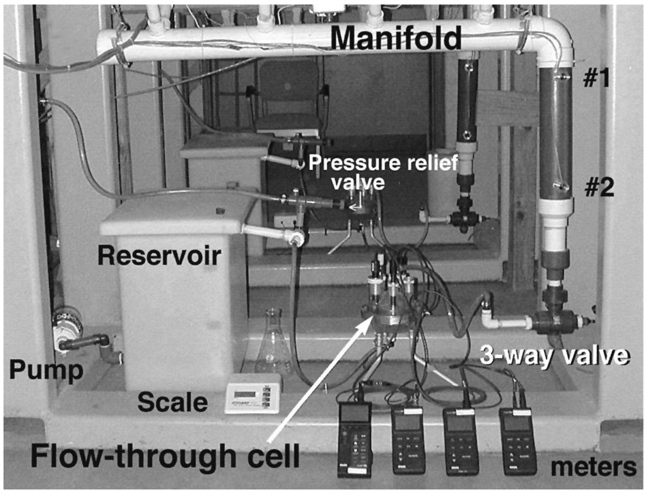
### Leachate Collection and Monitoring

Figures 4a and 4b illustrate the leachate collection system. Leachate from each of the eight 3.2 cm O.D. PVC drain tubes flowed into a 7.6 cm O.D. schedule 40 collection manifold header. The manifold was suspended by chains attached to the sides of the base stand, which thereby carried all of the manifold's weight. Therefore, the measurements obtained from the load cells were only for the weights of the bins plus their contents.

The volume of leachate produced could be measured using the assembly depicted in figure 4a. Each of the eight drain tubes had two valves (A and B in fig. 4a) upstream from the collection manifold. Prior to installation, this assembly was calibrated in order to determine the volumetric capacity of each tube, which averaged 142 mL. During normal operation, valve B was closed to pressurize the system for gas production measurement. Valve A remained open as leachate drained from the bin into the measurement assembly. With valve B closed, the level of the leachate rose until it reached valve A, then valve A was manually closed and valve B was opened to allow leachate to drain into the collection header. Leachate from the collection manifold flowed into a vertical 7.6 cm O.D. clear PVC column. Flow was stopped by a three-way valve. Once the column was filled, pressure measurements were collected using two pressure transducers installed exactly 30.48 cm on center from each other (designated as #1 and #2 in fig. 4b). The pressure transducer output could be used to calculate specific gravity of the leachate using the hydrostatic fluid law. However, since the system did




**(a)**




**(b)**

**Figure 4–Leachate collection system: (a) volume measurement apparatus and manifold; and (b) flow-through cell with probes and associated meters and leachate reservoir.**

not generate high volumes of leachate, no pressure measurements were recorded.

A three way valve following the vertical column allowed flow to be directed either into a 250 mL Geotech multi-port flow-through cell (fig. 4b) or drained for sample collection. One disadvantage of this system, discovered after the fact, was that although it worked well under continuous circulation, under batch conditions a small volume of residual leachate was left in the bottom of the vertical column due to its being lower in elevation than the flow-through cell.

The flow-through cell was instrumented with electrodes for measurements of pH, oxidation-reduction potential, dissolved oxygen, and electrical conductivity (fig. 4b). These instruments could potentially be input to a datalogger system, but for this project these data were manually recorded. The three way valve was placed upstream from the cell to allow the cell to fill and thus facilitate sample retrieval. Upon leaving the cell, leachate flowed into a 0.21 $m^3$ HDPE reservoir (fig. 4b). Beneath each reservoir was placed a 30 kg capacity scale for measuring the mass of leachate. Any pH adjustments could be performed on the leachate in this reservoir if desired. Leachate and added distilled water were then recirculated to the top of each bioreactor by a 62 W magnetic drive centrifugal pump. Pressure was regulated using a 34.5 to 344.6 kPa pressure relief valve (fig. 4b). Leachates from both bins were analyzed by the OARDC Laboratory (Wooster, Ohio) using standard methods (APHA, 1998).

### Temperature Monitoring

Temperatures within the bioreactor bins were monitored using Type T copper-constantan thermocouples. The 0.3-m-long thermocouples were sheathed in 0.16-cm-diameter stainless steel for corrosion protection. Eight thermocouples were manually positioned within the MSW matrix of each bin (fig. 1). These eight were arranged at two different levels in the MSW (30 cm and 60 cm above the bin floor). Both levels had the same pattern of one thermocouple on each end and two near the sidewall opposite the Plexiglas viewing window. Four additional thermocouples were located in the headspace between the upper soil layer and the HDPE cap, arranged in the same pattern as the lower two levels. Thermocouple output was collected every eight hours using a Hewlett Packard 3852 data acquisition system controlled via LabView interface.

### Mass Monitoring

Four 453 kg (1000 lbs) capacity load cells were positioned under all four corners of each bin. The load cells were rated for a maximum nonlinearity of ±0.25%, which was equivalent to ±1.1 kg (2.5 lbs.) per load cell or a cumulative ±4.5 kg (10 lbs) per bin. Their temperature effect was ±0.026%/°C, which was equivalent to a cumulative ±0.47 kg/°C per bin. Analog output signals from the individual load cells were summed for each bin and digitally displayed. Prior to installation, the load cells were zeroed and calibrated. Calibration is recommended on an annual basis by adding known weights to the bins and adjusting as needed. Upon initially setting up the system, the bins were elevated using a forklift and leveled. The bins were then slowly lowered to ensure that their weight did not overload any single load cell; this was important since each bin weighed approximately three times the load rating for any individual load cell. Load cell data were manually recorded on a weekly basis.

Initial mass of the MSW was determined by weighing the bins on a large platform scale first prior to the addition of MSW to get a tare value and again after the MSW had been added. The volume of MSW was calculated assuming rectangular geometry using the length and width of the bin and the depth of MSW above the gravel drainage layer. Density was determined by dividing the initial mass by the calculated volume for each bin.

### Moisture Addition

After all instrumentation was installed and checked, distilled water was applied to the bins on day 83 to bring them up to field capacity and thereby provide the moisture necessary for microbial activity. Water was applied to the bins until drainage was observed. Bin A required 24.5 kg of water and bin B required 39 kg of water to induce drainage. Accumulated leachate and an additional 13.5 kg of distilled water were applied on day 208 at bin B.

## Results and Discussion

The bulk composition of the MSW placed in the bins was characterized in this work (table 1) because generic information of MSW in landfills has broad ranges for different components. MSW bulk composition can reveal potential substrates for microbial decomposition and sources for landfill gas. The two most readily biodegradable fractions, yard waste and food waste, were relatively low (less than 5%), suggesting that landfill gas production would be severely limited by the lack of precursors. In contrast, paper and plastics constituted 70% of the MSW. Cellulolytic organisms would be expected to play a major role in the breakdown of polymers because cellulose-containing substrates (paper, cardboard) accounted for over 50% of the initial bulk composition. About 10% of the MSW was comprised of inorganic components that are not biodegradable but could be potential long-term sources of metals in leachates.

The MSW contained high levels of cellulose and hemicellulose (table 2). This was in agreement with the high percentage of paper and cardboard found in the samples. However, elemental analysis of C was not consistent with the high cellulose and hemicellulose content; the source of this discrepancy is unknown but may

**Table 1. Characterization of MSW in landfill bins**

| Component | % (wt/wt) | Moisture Content (%) |
|---|---|---|
| | Organic | |
| Food waste | 2.0 | 51 |
| Paper | 49 | 62 |
| Cardboard | 8.1 | 16 |
| Plastics | 21 | 3.2 |
| Textiles | 4.8 | 13 |
| Rubber | 0.3 | 1.8 |
| Yard waste | 2.1 | 7.1 |
| Wood | 2.5 | 13 |
| | Inorganic | |
| Glass | 0.5 | 0.2 |
| Tin cans | 5.6 | 1.3 |
| Aluminum | 0.7 | 4.2 |
| Other metals | 0.4 | 2.6 |
| Soil, ash | 3.2 | 52 |
| Total | 100 | N/A* |

* Not applicable.

**Table 2. Partial chemical analysis of MSW**

| | Concentration (% wt/wt) | | | |
|---|---|---|---|---|
| Analyte | Bin A | Bin B* | Average | S.D. |
| Carbon | 7.6 | 1.5 | 4.6 | 4.3 |
| Hydrogen | 1.1 | 0.2 | 0.7 | 0.6 |
| Oxygen | 8.4 | 1.7 | 5.1 | 4.7 |
| Nitrogen | < 0.01 | 0.01 | N/A† | N/A |
| Sulfur | < 0.01 | < 0.01 | N/A | N/A |
| Phosphorus | 0.01 | 0.02 | 0.02 | 0.01 |
| C:N ratio | > 760 | 150 | 455 | 431 |
| Cellulose | 54.5 | 20.0 | 37.3 | 24.4 |
| Hemicellulose | 32.2 | 11.8 | 22.0 | 14.4 |
| Lignin | < 0.1 | < 0.1 | N/A | N/A |
| Protein | < 0.06 | 0.06 | N/A | N/A |

* Bin B was sampled before sludge addition.
† Not applicable (insufficient data).

reflect problems of representative sampling of the heterogeneous material. Protein was practically non-existent at or below 0.06%. The lignin content was low (< 0.1%) and represents a refractory fraction that is mostly decomposed through fungal attack. The C:N ratio was very high, ranging from 150 to over 760. This high ratio was due to a very low N content, which, in the case of one sample, was below detection limits. For all analytes, the standard deviation was nearly equal to the average value, again demonstrating the heterogeneity of MSW.

After placement into the bins, the MSW was compacted to 332 kg/m$^3$ for the bioreactor with sewage sludge addition and 324 kg/m$^3$ for the control. The density of normally compacted MSW in a landfill ranges from 362 to 498 kg/m$^3$ (Tchobanoglous et al., 1993), but these measurements vary greatly depending on geographical location. The low density of the MSW in the bioreactor bins may be due to the high plastic content.

Partial chemical analysis of the dewatered sludge added to bioreactor bin B is reported in table 3. The sludge was within average ranges for most constituents (USEPA, 1979), but had an elevated zinc concentration of 2260 mg/kg as compared with a U.S. median of 1700 mg/kg (USEPA, 1984). This was attributed to the use of zinc phosphate as an anticorrosion agent in the water mains of the metropolitan Columbus area.

The C:N ratio for the sludge was 10:1, and the calculated overall C:N ratio for sludge amended bin B was 381, assuming an average C:N ratio of 455 for the MSW in both bins. It was not within the scope of this experiment to change the C:N ratio by nitrogen supplementation. Additionally, much of the carbon substrate was relatively recalcitrant due to the presence of plastics and cellulose polymers and the low (unshredded) surface area to volume ratio. Thus it was unlikely that nitrogen amendments would have overcome this constraint. Furthermore, gas production was negligible over the entire time course, as monitored with the Tedlar sampling bags. These data together further support the lack of biodegradation of the MSW.

Black precipitates formed in the leachates which had accumulated in several drain tubes, and two samples were removed from the drains to determine the presence of sulfate-reducing bacteria. Their densities were as high as $10^4$ bacteria/mL leachate, estimated by a most probable number technique with lactate as the electron donor and carbon source. The black precipitates were believed to comprise Fe-sulfides produced as the result of the bacterial sulfate reduction. No further microbiological analysis was performed in this first phase of the project.

Table 4 summarizes the results of the partial chemical analysis of the leachate samples from bins A and B. Sewage sludge amendment (bin B) increased the concentration of total suspended solids (TSS) and decreased the redox potential to negative values when compared to bin A data. Calcium, magnesium, potassium, and sodium were the main cations in both leachate samples, and chloride, nitrate, and sulfate were the main anions. The presence of relatively high nitrate concentrations suggested the lack of denitrification activity. The $BOD_5$ was below 5 mg/L, but COD values were about 40-fold higher, suggesting the presence of recalcitrant molecules and lack of biological decomposition. The concentrations of toxic and other heavy metals were generally less than 0.3 mg/L with the exception of

**Table 3. Partial chemical analysis of sludge added to bin B**

| Analyte | Value* |
|---|---|
| Total solids (TS, %) | 18.5 |
| Volatile solids (% of TS) | 71 |
| Conductivity (mmhos/cm) | 6.3 |
| pH | 6.0 |
| Metals (mg/kg) | |
| Arsenic | < 9.66 |
| Cadmium | 1.6 |
| Calcium | 18 600 |
| Chromium | 33.0 |
| Copper | 230 |
| Lead | 72.0 |
| Magnesium | 5 200 |
| Mercury | < 4.83 |
| Molybdenum | 28.4 |
| Nickel | 29.0 |
| Selenium | 2.68 |
| Zinc | 2 260 |
| Nutrients (% of dry weight TS) | |
| Nitrogen, ammonium | 2.0 |
| Nitrogen, nitrate | 0.03 |
| Nitrogen, organic | 3.7 |
| Nitrogen, total Kjeldahl | 5.7 |
| Phosphorus | 2.0 |
| Potassium | 0.51 |
| C:N Ratio | 10:1 |

* Values on a dry weight basis.

**Table 4. Partial chemical analysis of leachate samples after 13 months of operation**

| Analyte | Bin A | Bin B |
|---|---|---|
| TSS (mg/L) | 1320 | 1880 |
| Redox potential (mV)* | 110 | –20 |
| pH* | 7.2 | 7.1 |
| Conductivity (mmhos/cm)* | 1140 | 1480 |
| COD (mg/L) | 201 | 180 |
| $BOD_5$ (mg/L) | 2.7 | 4.8 |
| Salinity (%)* | 1.18 | 1.51 |
| Chlorine (mg/L) | 246 | 325 |
| Nitrate (mg/L) | 64.6 | 11.8 |
| Ammonium-N (mg/L) | 30.5 | 63.2 |
| Phosphate (mg/L) | 1.9 | < 0.1 |
| Sulfate (mg/L) | 155 | 495 |
| Aluminum (mg/L) | 0.08 | 0.08 |
| Arsenic (mg/L) | 0.07 | < 0.04 |
| Bismuth (mg/L) | 0.79 | 0.77 |
| Boron (mg/L) | 0.08 | 0.08 |
| Calcium (mg/L) | 179 | 164 |
| Cobalt (mg/L) | < 0.01 | 0.01 |
| Chromium (mg/L) | 0.006 | 0.007 |
| Iron (mg/L) | 0.04) | 0.13 |
| Lithium (mg/L) | 0.03 | 0.09 |
| Magnesium (mg/L) | 28.4 | 99.2 |
| Manganese (mg/L) | 0.70 | 0.55 |
| Molybdenum (mg/L) | < 0.01 | 0.03 |
| Nickel (mg/L) | 0.02 | 0.02 |
| Phosphorus (mg/L) | 0.56 | 0.16 |
| Potassium (mg/L) | 220 | 139 |
| Silicon (mg/L) | 16.7 | 18.0 |
| Strontium (mg/L) | 1.18 | 2.21 |
| Sodium (mg/L) | 60.8 | 203 |
| Sulfur (mg/L) | 47.2 | 170 |
| Vanadium (mg/L) | 0.013 | 0.018 |
| Zinc (mg/L) | 0.27 | 0.03 |

* Data averaged from samples retrieved from individual drain tubes.

Note: The following elements were below the level of detection (in mg/L): beryllium (< 0.002), bromine (< 0.1), cadmium (< 0.002), copper (< 0.01), fluorine (< 0.1), and selenium (< 0.1).

strontium and bismuth (table 4). Dissolved oxygen sensors had been included in the flow-through cell instrumentation, but were not used because of the unanticipated lack of continuous leachate flow.

During the initial process of bringing the MSW up to field capacity, point applications of water were applied above the soil layer. It was observed that the resultant leachate preferentially flowed to drains laterally distant from the point of application. Preferential flow patterns were also observed under uniform applications of water and leachate on days 83 and 208. Some drain tubes filled much more rapidly than others; for example drain 4 from bin B never collected any leachate.

Water balance components included (1) MSW moisture content, (2) soil moisture, (3) leachate, (4) water formed during microbial decomposition, and (5) water lost through gas emissions. Initial MSW and soil moisture contents were measured prior to placement and were 34.4% and 13.2%, respectively.

Figure 5 shows the changes in temperature over time for both bins. The noise in these temperature signals may be attributed to the draftiness of the laboratory, the variability of the HVAC system, and the effect of the large continuously exhausting fume hood. Heat generation in the bins could not be unequivocally discerned from these data. Figure 6 illustrates cross-sectional thermal isopleths on days 5 and 52. The thermal isopleth patterns reflect the heterogeneity of the MSW, and may also be affected by preferential flow patterns, variable thermal conductivities, and non-uniform distribution of biodegradable MSW constituents (i.e., heat sources).

Settlement in the bins was noted through the Plexiglas windows, and measured at 50 mm intervals along the width of the window. The upper boundaries of MSW, sludge (for bin B), and soil were initially traced upon the Plexiglas with a permanent marker. After 450 days of operation, the amount of MSW settlement ranged from 39 to 95 mm in bin A (mean 67 mm), and from 32 to 80 mm in bin B (mean 52 mm). This observed settlement was due to the combined effect of gravity compaction and slight biological decomposition of MSW. With the data available, it was impossible to differentiate between settlement factors.

Changes in mass of the bins are presented in figure 7. The mean values of mass for bins A and B were 1359 kg and 1368 kg, respectively. Overall, the change in mass was 1.3% for bin A and 1.0% for bin B, defined as $(M_{max} - M_{most\ recent})/M_{mean}$. This small decrease was in agreement with negligible microbial decomposition and lack of heat production.

## Discussion of Novel Design Components and Recommended Improvements to Design

The strengths of this design included the use of multiple underdrains, subsurface irrigation, load cells, flow-through cell, the ease of physical access, and the ability to continuously monitor temperatures across the MSW. Mass data could also have been continuously monitored, but were not for this experiment. The 1.5 $m^3$ size bins allowed use of unshredded MSW but approached the limits of the available fork lift and pickup truck; a larger design would not be feasible to lift and transport to the laboratory. The performance of the subirrigation system and flow-through cell could not be evaluated in this study due to low microbial activity and thus low leachate production.

The HDPE-lined steel bins were difficult to make airtight because of the number of holes drilled in the HDPE to secure it to the steel. A better design would be to use a prefabricated HDPE container with factory installed sampling ports and drains. Exterior steel framing could then be built around the container to handle the MSW pressure exerted on the sidewalls. Sealing the top of the bin could be accomplished by heat-welding an HDPE lid into place.

Leachate distribution was accomplished by a subirrigation system at the soil-waste interface in this study. Further research is needed to determine the best method for applying leachate and water to bioreactor landfills. Use of a spray irrigation system above the soil would avoid the potential problem of plugging by soil particles. However, one of the disadvantages of spray irrigation at the field scale is aerial drift. There are air quality and safety issues associated with the spray irrigation of leachate on the field scale that would need to be addressed. Biofouling of the soil layer could also be a potential long-term problem with spray irrigation. Biofouling and plugging of nozzles and holes in irrigation laterals may cause problems for either spray or subirrigation systems. Other alternatives include infiltration ponds, open horizontal trenches, horizontal trenches filled with infiltration material, trickle irrigation, vertical infiltration wells, and vertical well clusters.

More insulation beyond the 25-mm-thick polystyrene top and sides, such as an insulated bottom panel with drain outlet holes, would yield a higher overall R-value and would reduce heat loss across the bin wall boundaries. In comparison, use of 50-mm-thick polystyrene to encase the bioreactor vessel has been reported in composting research literature (Hansen et al., 1993). Further research is needed to determine the minimum R-value appropriate for bioreactor landfills of this scale.

## Conclusions

A laboratory-scale (1.5 $m^3$) bioreactor system was designed to simulate anaerobic microbial processes in landfills. The system was designed to provide for gas collection, leachate recirculation, and moisture addition. The bioreactors were kept indoors to eliminate climate and weather effects and to facilitate data collection. An outdoor facility was also excluded by virtue of potential vandalism. The overhead area in the laboratory was retrofitted with an exhaust hood as a precaution against accidental escape of combustible and noxious gas. A platform with a stairway and handrails was constructed to facilitate safe access to the bioreactors. Following the construction, the bioreactor bins were loaded with fresh, unsorted, unshredded MSW from a sanitary landfill. The bins were instrumented to monitor temperature, mass, leachate production, and preferential flow of leachate within the heterogeneous waste material. Negligible decomposition was observed in the landfill bioreactor bins as judged by temperature and mass loss measurements and by the lack of landfill gas production. MSW sorting and characterization revealed a high proportion (> 70% dry wt. basis) of paper and plastics and a high C:N ratio in the bins, which was deemed to account for the lack of active biodegradation and landfill gas production. A 5:1 (by wet weight) amendment of MSW

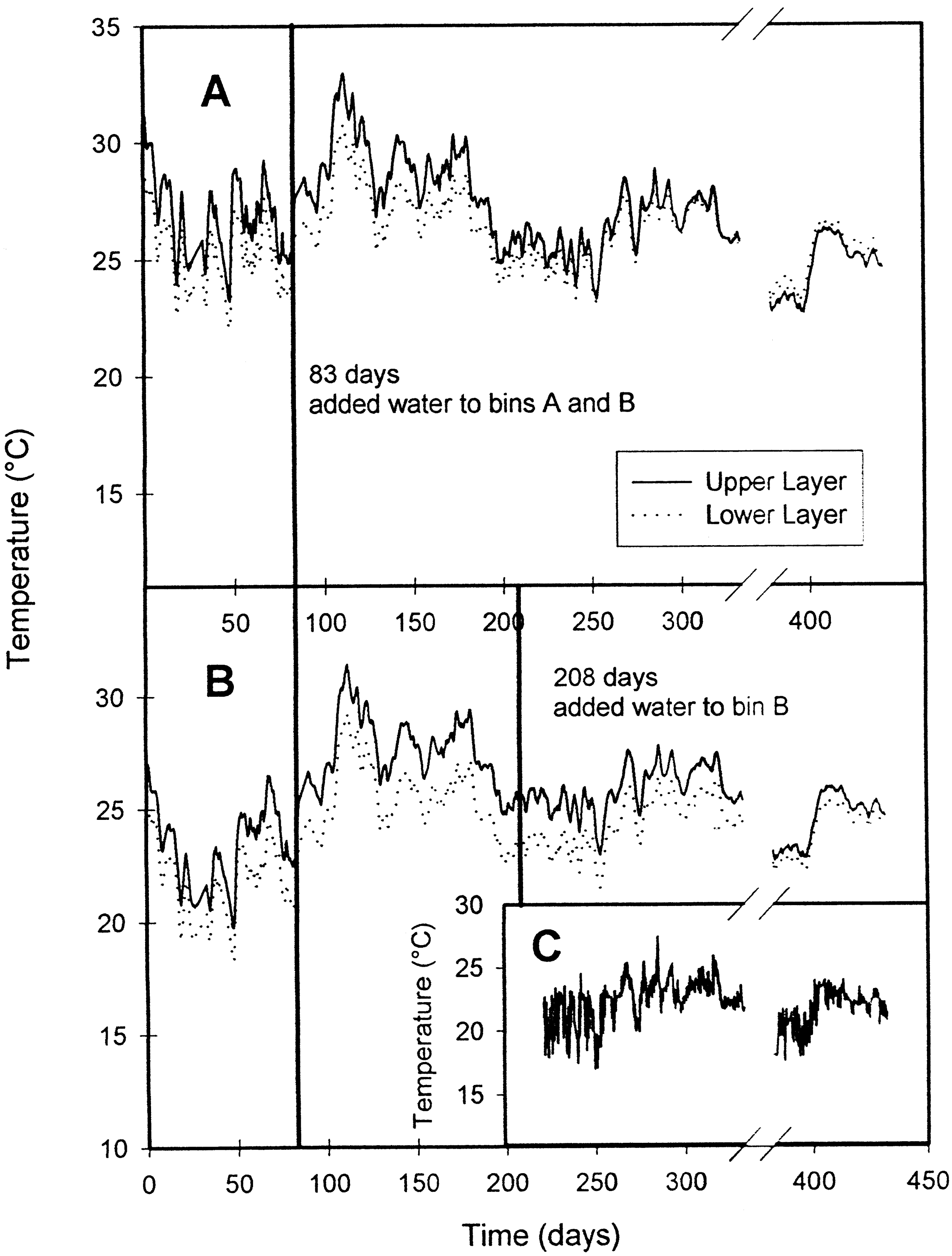



**Figure 5–Temperatures within bins A and B and in ambient room air (C). The lower and upper layer thermocouples were located at 30 cm and 60 cm above the bin floor, respectively. Due to datalogger failure, no data were recorded between 334 and 382 days.**

with a single layer of dewatered sewage sludge did not enhance the biodegradation although it provided for additional inoculum. The C:N ratios were in the range of 380 to 455, suggesting that microbial growth and hence the biomass and activity were N-limited, although the role of other key nutrients (e.g., biologically available phosphorus) cannot be ruled out. This experimental phase resulted in several conceptual and practical refinements to the bin design. As improvements are incorporated into the bioreactor design, they may be overridden by microbiologically recalcitrant fractions of MSW. In an experimental scale such as this study, MSW sorting and shredding would help improve the biodegradability but would be most unrealistic in full-scale landfill operation.

The strengths of this first generation design could not be demonstrated with microbial decomposition and landfill

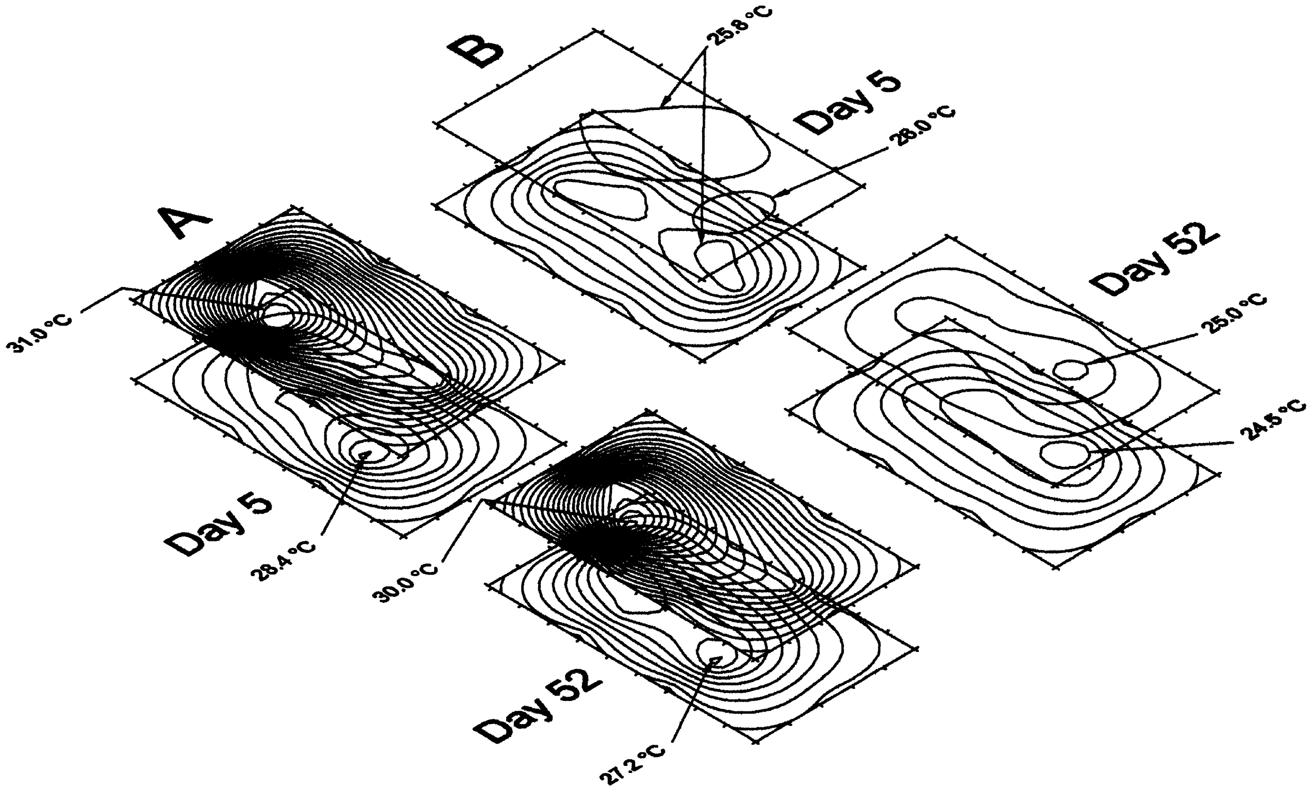



**Figure 6–Isometric view of temperature isopleth cross-sections of landfill bioreactor bins A and B on days 5 and 52. Temperature isopleth interval is 0.2°C, descending from the interior maximum. Each tick mark interval along the perimeter represents 0.2 m.**

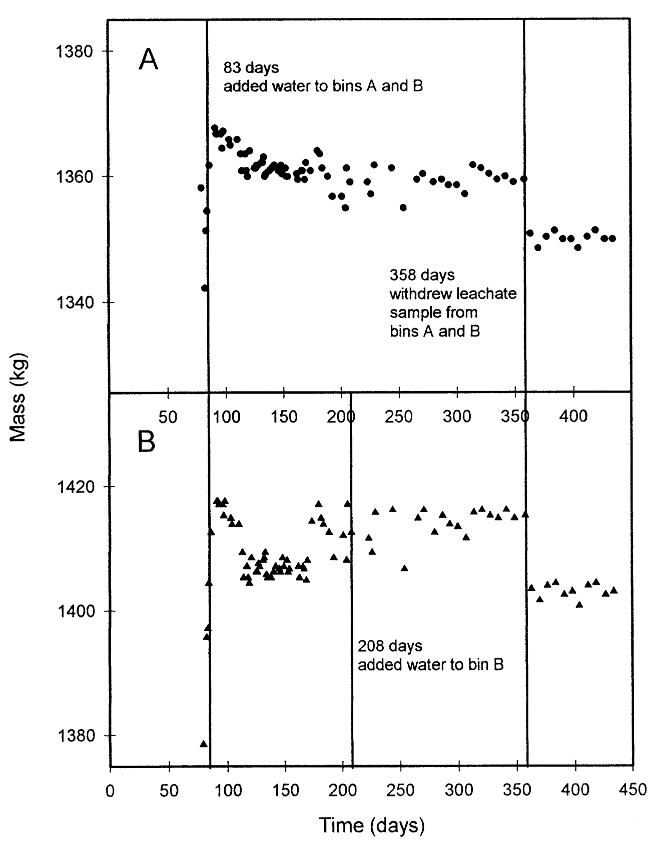



**Figure 7–Mass of bins A and B.**

gas data, because the MSW randomly chosen for the bins was not conducive to fast biodegradation. Substrate decomposition is a prerequisite for any active bioreactor landfill and thus it remains a central issue in managing bioreactor landfills. To date, nutrient availability in MSW landfills remains unclear because total nutrient analysis does not reflect their availability to support microbial growth. Substrate composition and nutrient availability can have overwhelmingly negative impacts on microbial dynamics and decomposition kinetics in bioreactor landfills. These concerns about biodegradable MSW, unprecedented under conventional landfill dry entombment practices, pose a challenge to bioreactor landfill management. Research addressing these concerns in bioreactor landfill technology should benefit from laboratory bin sizes of the scale used in this study because this design overcomes many artificial effects inherent to small scale vessel and column systems.

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